Light Sources.
Brightness and Insertion Devices

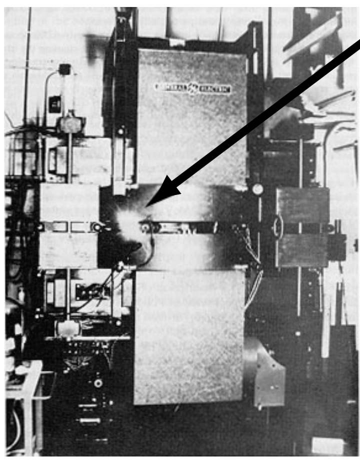
Fernando Sannibale

Thanks to Herman Winick and David Robin

Introduction

- **Electron accelerators were initially developed to probe elementary (subnuclear) particles for the study of the fundamental nature of matter, space, time, and energy.**

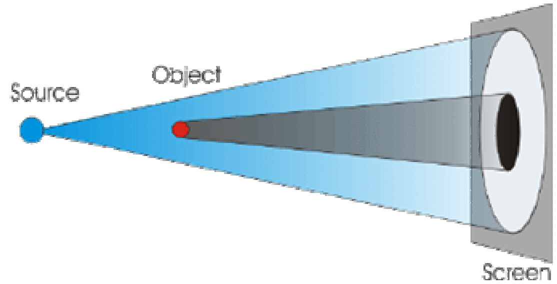
- **The first time synchrotron radiation was observed in an accelerator was in 1947 from the 70 MeV electron beam at the General Electric Synchrotron in New York State.**



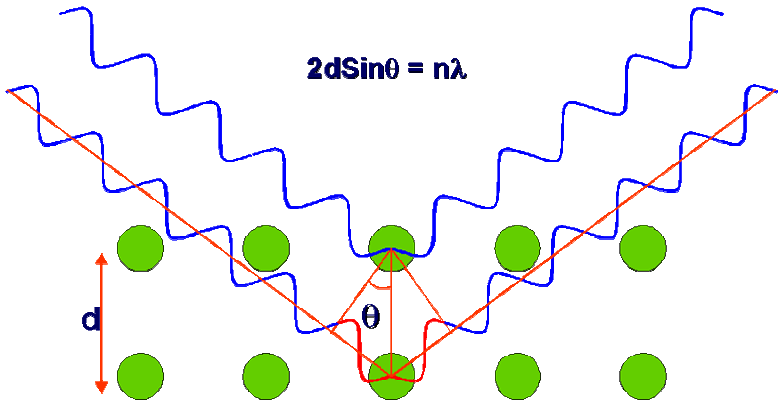
In the earlier times, synchrotron radiation was just considered as a waste product limiting the performance achievable with lepton machines.

- **However other researchers soon realized that synchrotron radiation was the brightest source of infrared, ultraviolet, and x-rays, and that could be very useful for studying matter on the scale of atoms and molecules.**

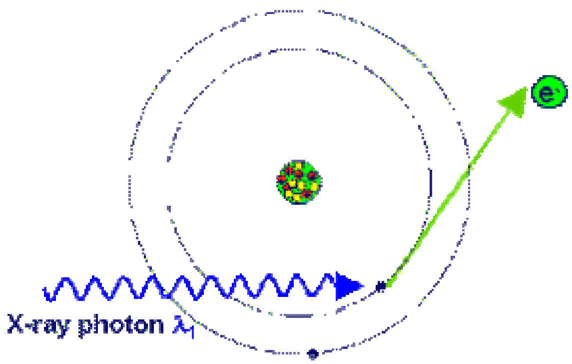
Interaction of Photon's with Matter



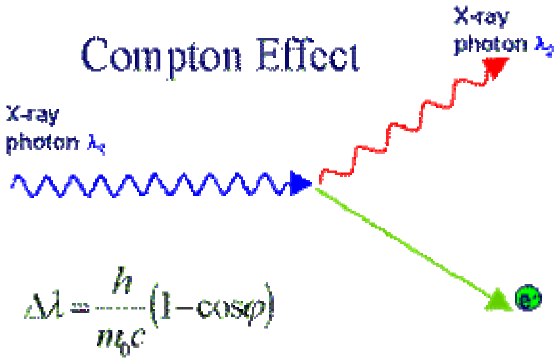
Radiography



Diffraction



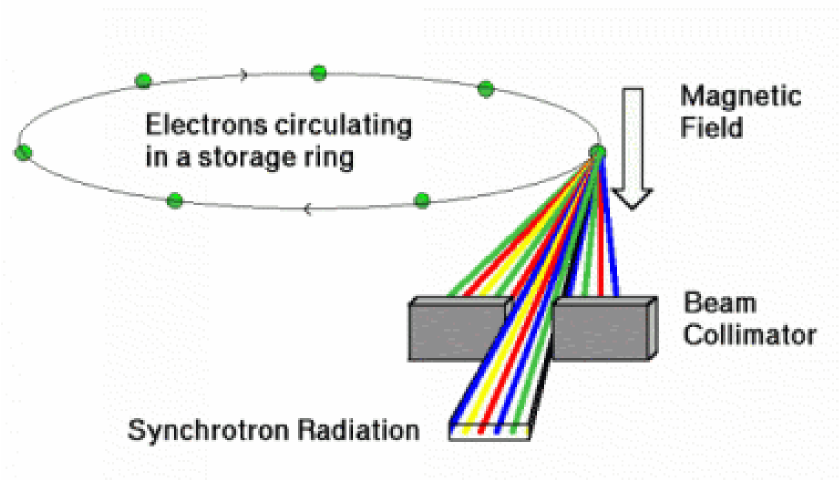
Photoelectric Effect



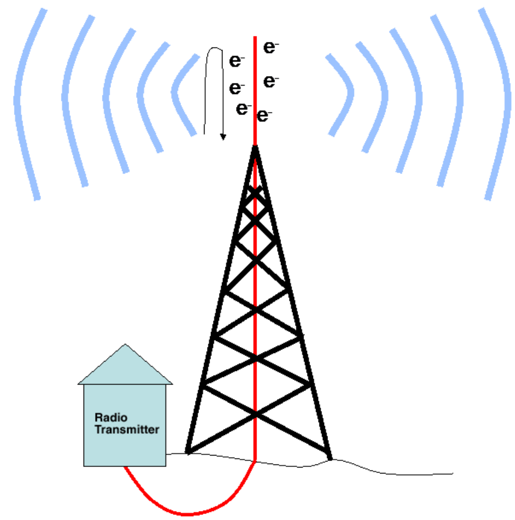
Compton Scattering

What is Synchrotron Radiation?

- **We already showed that synchrotron radiation is electromagnetic radiation emitted when charged particles are radially accelerated (move on a curved path).**



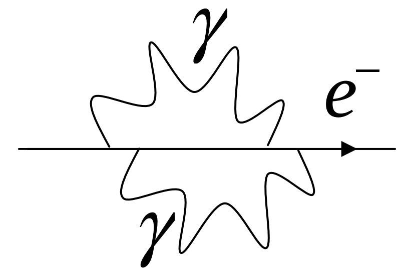
Electrons accelerating by running up and down in a radio antenna emit radio waves (long wavelength electromagnetic waves)



Both cases are manifestation of the same physical phenomenon:
***Charged particles radiate when accelerated*.**

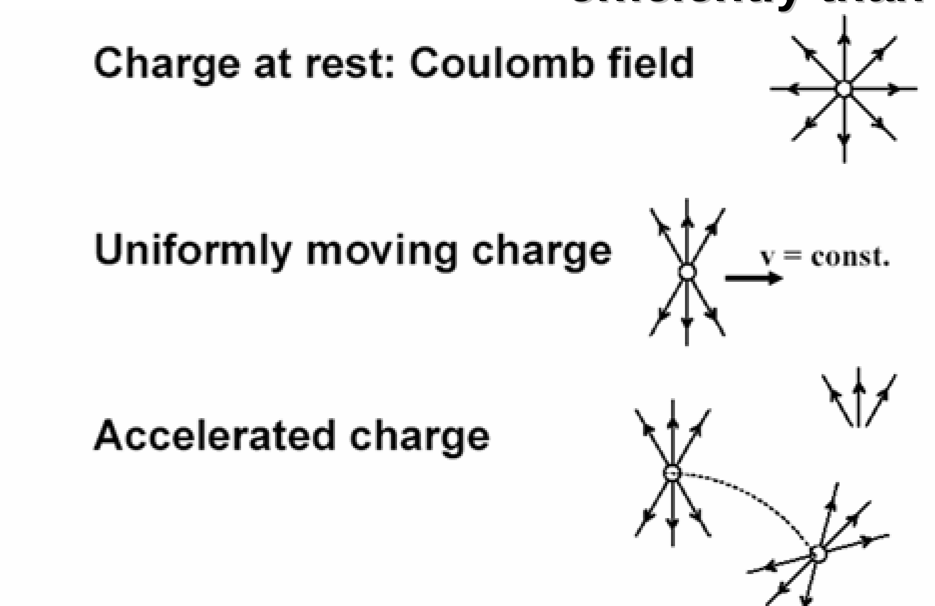
Why Do Particles Radiate under Acceleration?

- **We already saw that according to quantum field theory, a particle moving in the free space can be considered as “surrounded” by a cloud of virtual photons that appear and disappear and that indissolubly travel with it.**



- **When accelerated, the particle receives a “kick” that can separate it from the photons that become real and independently observable.**

- **Lighter particles are “easier” to accelerate and radiate photons more efficiently than heavier particles.**

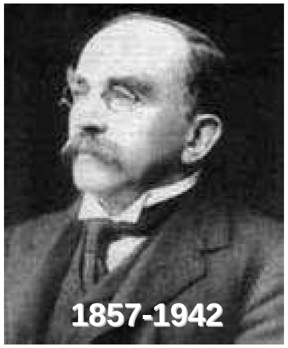


In the field of the magnets in a synchrotron, charged particles moves on a curved trajectory. The transverse acceleration, if strong enough, allows for the separation and *synchrotron radiation* is generated.

The Classical Picture

- The description of synchrotron radiation presented in the previous viewgraph made use of quantum field theory.

- Historically, the whole theory was developed well before quantum mechanics was even conceived:



- in **1897 Joseph Larmor** derived the expression for the instantaneous total power radiated by an accelerated charged particle.

$$P = \frac{q^2}{6\pi\varepsilon_0 c^3} a^2$$

Larmor Power

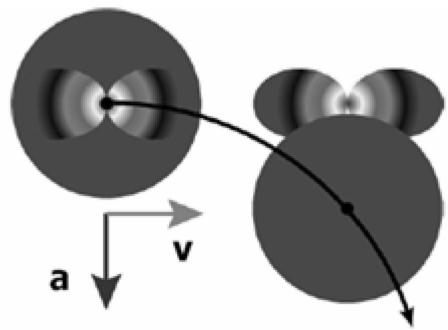
1898 Liénard:

ELECTRIC AND MAGNETIC FIELDS PRODUCED BY A POINT CHARGE MOVING ON AN ARBITRARY PATH

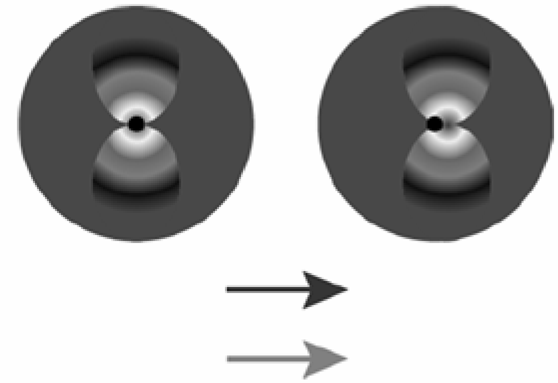
(by means of retarded potentials)

- and in **1898 Alfred Lienard** (before the relativity theory!) extended Larmor's result to the case of a relativistic particle undergoing centripetal acceleration in a circular trajectory

Longitudinal vs. Transverse Acceleration



Radiation field quickly separates itself from the Coulomb field



Radiation field cannot separate itself from the Coulomb field

$$P_{\perp} = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\gamma^2\left(\frac{d\mathbf{p}_{\perp}}{dt}\right)^2$$

$$\cancel{P_{\parallel} = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\left(\frac{d\mathbf{p}_{\parallel}}{dt}\right)^2}$$

negligible!

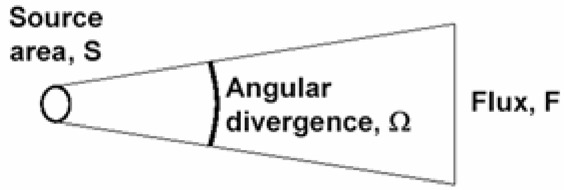
$$\boxed{P_{\perp} = \frac{c}{6\pi\varepsilon_0} q^2 \frac{(\beta\gamma)^4}{\rho^2} \qquad \rho = curvature\ \ radius}$$

- **Radiated power for transverse acceleration increases dramatically with energy. This sets a practical limit for the maximum energy obtainable with a storage ring, but makes the construction of synchrotron light sources extremely appealing!**

The Brightness of a Light Source

- In one of the previous lectures, we already dealt with the concept of brightness and showed how this quantity is the one of the main parameters for the characterization of a particle source.
- We remind that *brightness is defined as the density of particle on the 6-D phase space*.
  - The same definition applies to the photon case, just taking into account that photons are bosons and that the Pauli exclusion principle does not apply.
    - This is an important advantage because, at least from the point of view of quantum mechanics, no limitation to achievable photon brightness exists.

$$\text{Brightness} = \frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$$

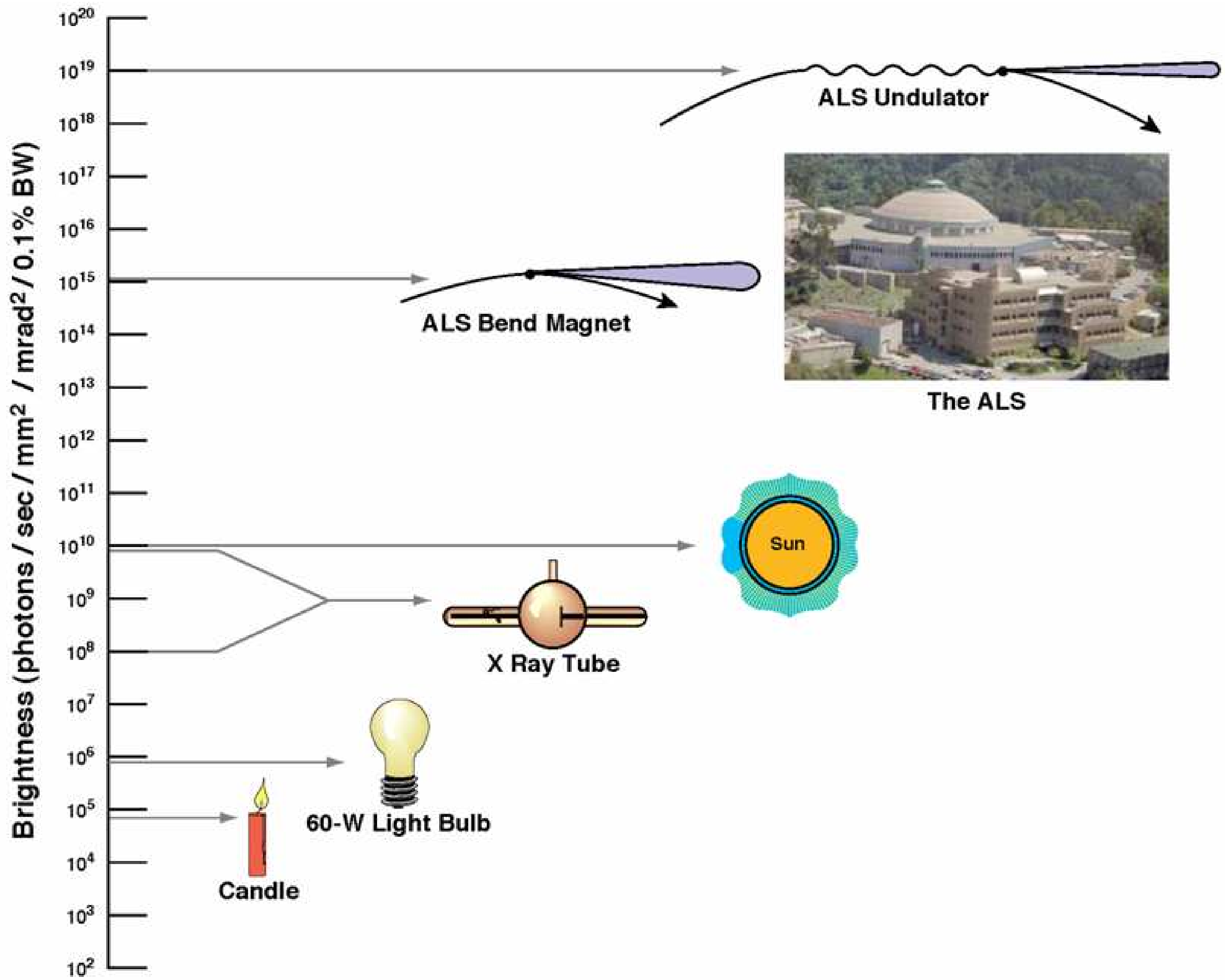


$$\text{Flux} = \frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec}}$$

$$Flux = \frac{d\dot{N}}{d\lambda} = \int Brightness\, dS\, d\Omega$$

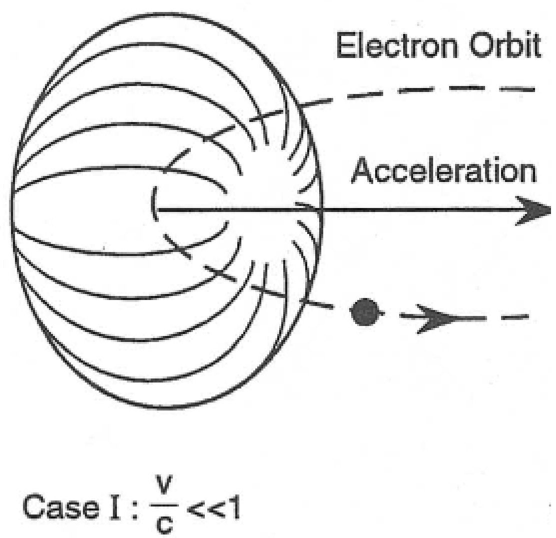
- From the above definitions, one can see that for a given flux, sources with a smaller emittance will have a larger brightness.

How Bright is a Synchrotron Light Source?

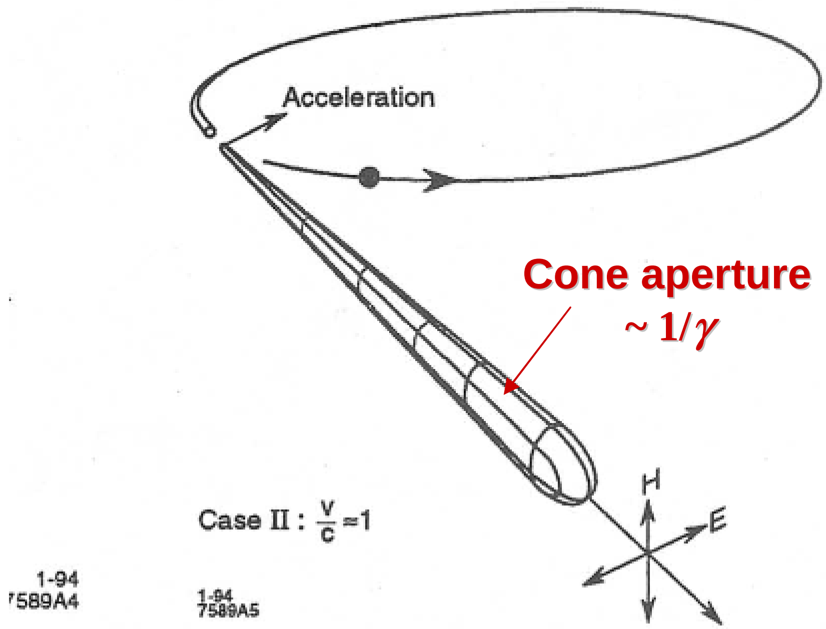


Synchrotron Radiation Angular Distribution

- **Radiation becomes more focused at higher energies.**



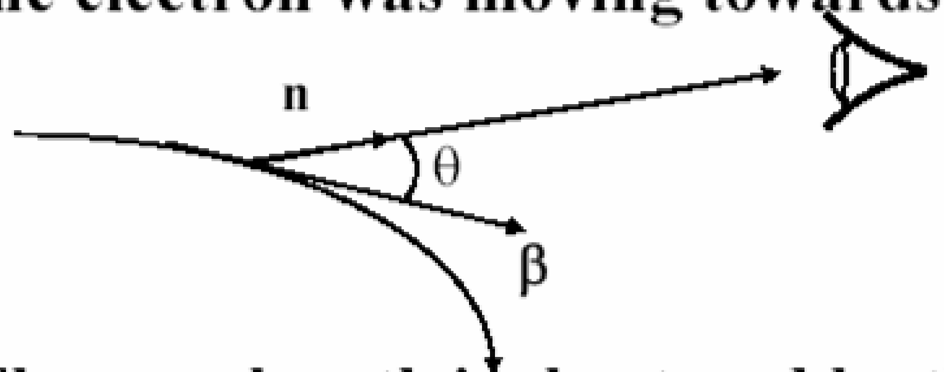
At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern



When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward.

Time Compression

Electron with velocity β emits a wave with period T_{emit} while the observer sees a different period T_{obs} because the electron was moving towards the observer



$$T_{obs} = (1 - \mathbf{n}\cdot\boldsymbol{\beta})\,T_{emit}$$

The wavelength is shortened by the same factor

$$\lambda_{obs} = (1 - \beta\cos\theta)\,\lambda_{emit}$$

in ultra-relativistic case, looking along a tangent to the trajectory

$$\boxed{\lambda_{obs} = \frac{1}{2\gamma^2}\lambda_{emit}}$$

since

$$\boxed{1 - \beta = \frac{1-\beta^2}{1+\beta} \cong \frac{1}{2\gamma^2}}$$

Typical Band-Width Of Synchrotron Light

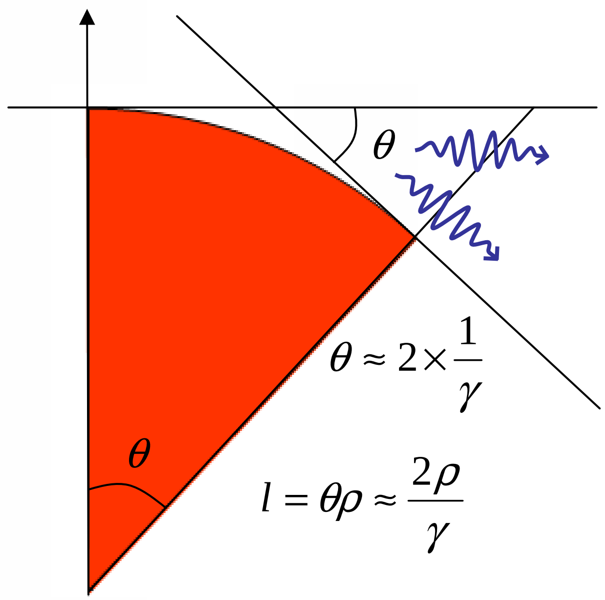
Due to extreme collimation of light

- observer sees only a small portion of electron trajectory **(a few mm)**

$$l \sim \frac{2\rho}{\gamma}$$

- Pulse length: difference in times it takes an electron and a photon to cover this distance

$$\Delta t \sim \frac{l}{\beta c} - \frac{l}{c} = \frac{l}{\beta c}(1-\beta) \quad \Longleftrightarrow \quad \Delta\omega = \frac{1}{\Delta t}$$



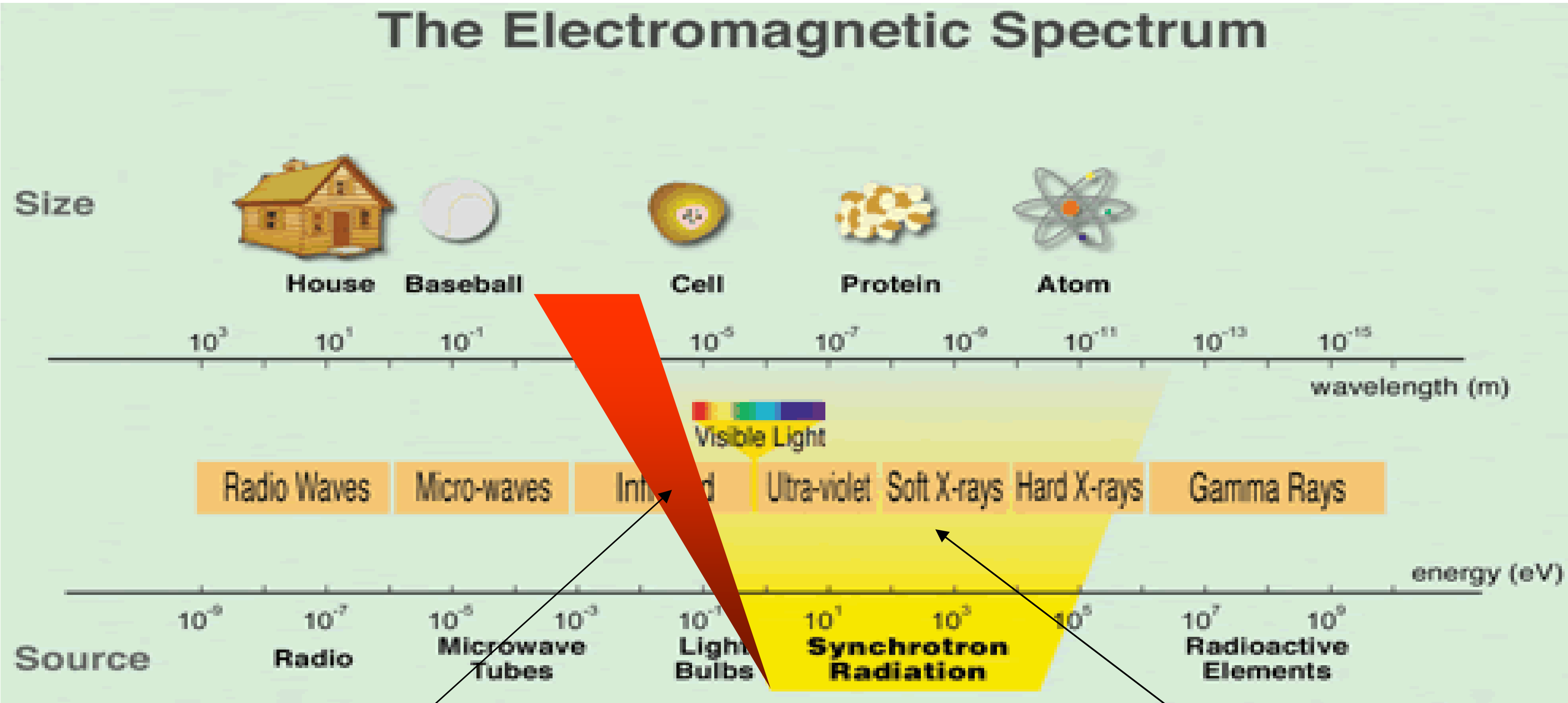
- **Example for an electron ring with 1.9 GeV and with a bending radius of 5 m:**

$$l \cong 2.7\ mm \Rightarrow \Delta t \cong 3.2\times10^{-19}\ s \Rightarrow \Delta\omega \cong 3.1\times10^{18}\ s^{-1}$$

$$\boxed{f_{MAX} \approx \frac{\Delta\omega}{2\pi} \cong 4.9\times10^{17}\ Hz \Leftrightarrow \lambda_{MIN} = \frac{c}{f_{MAX}} \cong 0.61\ nm}$$

Very broad band!

Synchrotron Radiation
Electromagnetic Spectrum

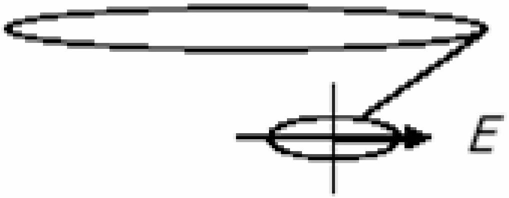


Coherent Synchrotron Radiation
THz Synchrotron Light Sources

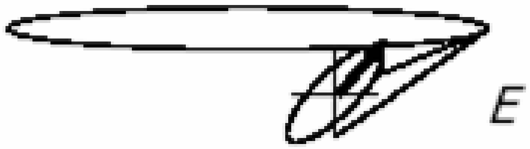
Synchrotron Light Sources

Polarization

Synchrotron radiation observed in the plane of the particle orbit is horizontally polarized, i.e. the electric field vector is horizontal



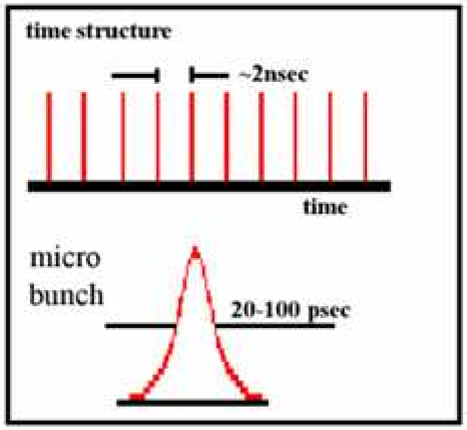
Observed out of the horizontal plane, the radiation is elliptically polarized



What Properties Make Synchrotron Radiation so Useful?

Recapitulating the main properties of synchrotron radiation:

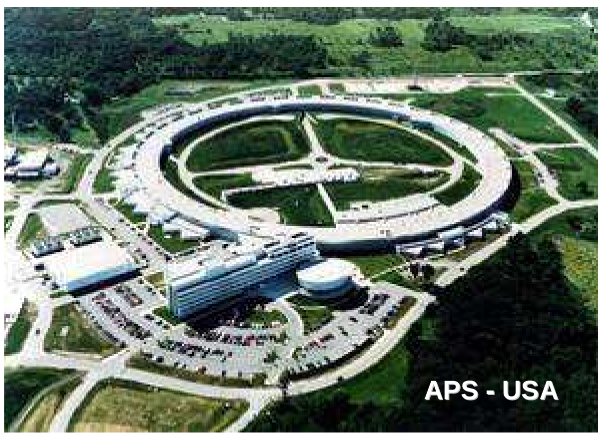
- **High brightness and flux**
- **Wide energy spectrum**
- **Highly polarized and short pulses**

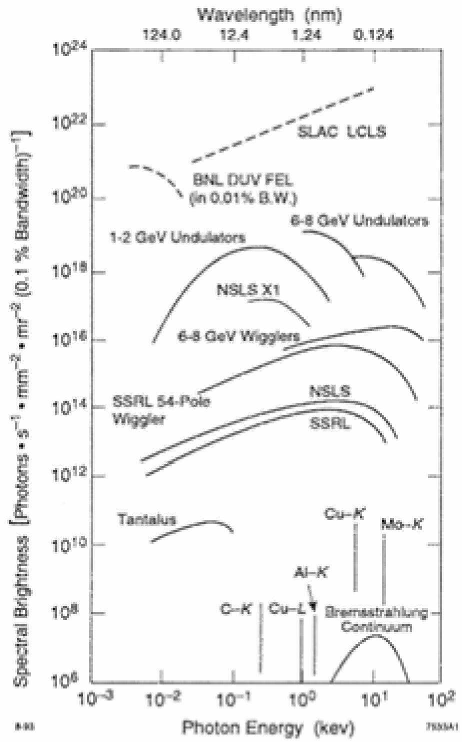


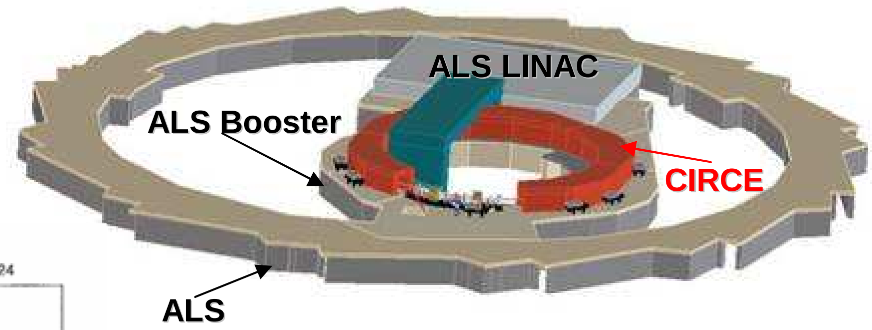
SR offers many characteristics of visible lasers but into the x-ray regime!

- **Partial coherence**
- **High Stability**

How to Exploit Synchrotron Radiation





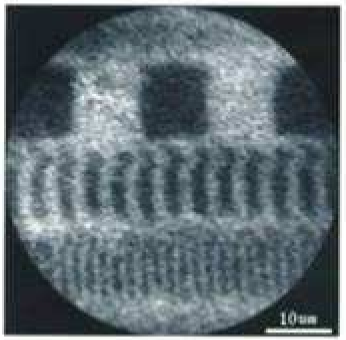


Modern synchrotron light sources are accelerators optimized for the production of synchrotron radiation.

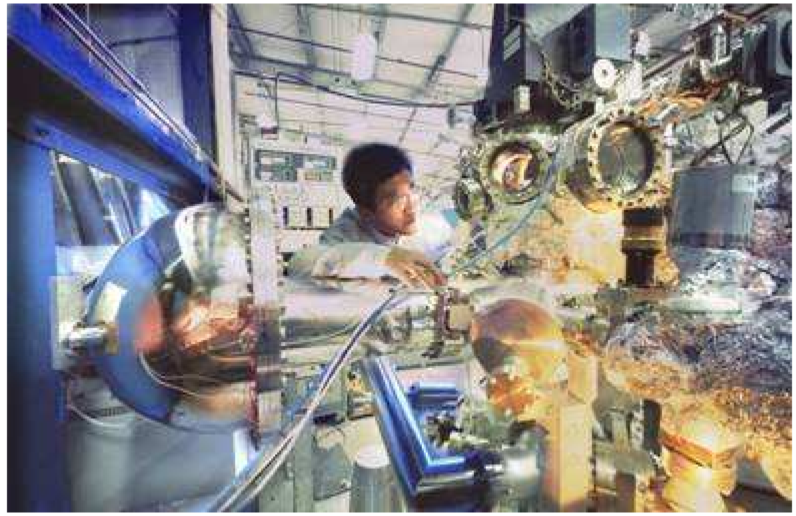
Applications

- Medicine
- Biology
- Chemistry
- Material Science
- Environmental Science
- and much more

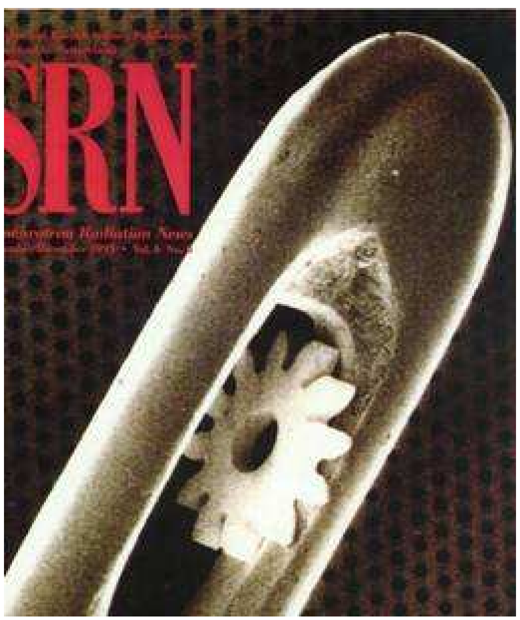
Materials Science

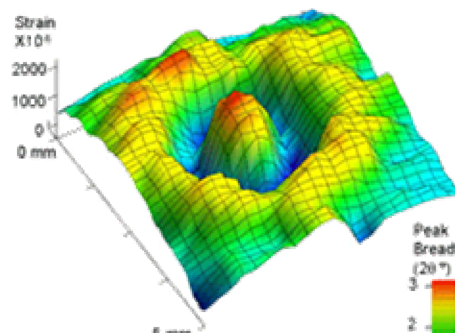


Visualizing magnetic bits on a computer hard drive

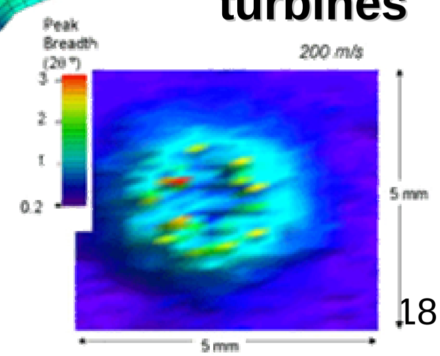


Using SR to learn how high temperature superconductors work





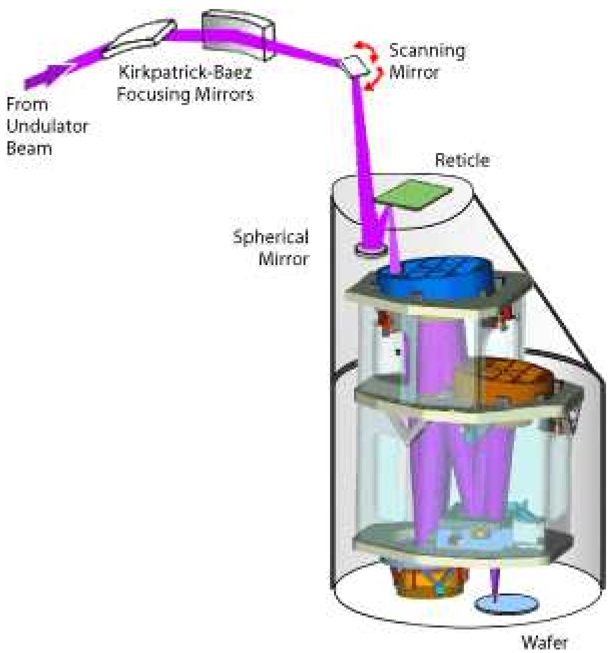
Understanding how debris causes damage to aircraft turbines

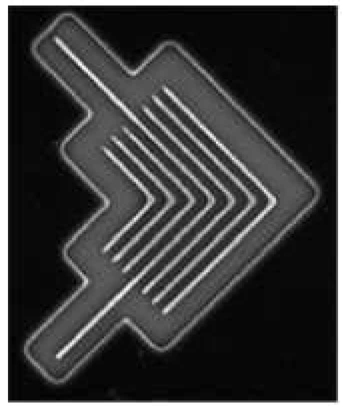


Using SR to make miniature mechanical and electromechanical devices

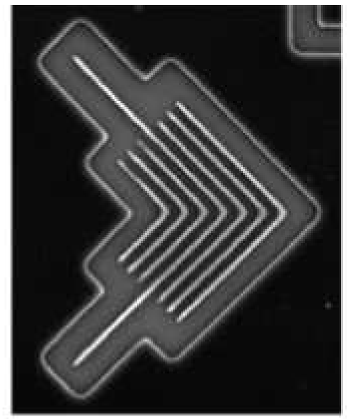
Next generation of semiconductors

EUV Lithography



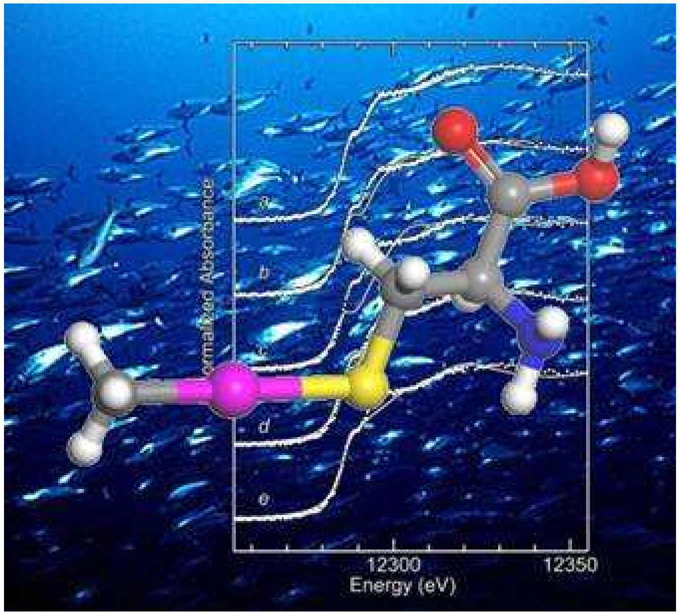


45 nm 3:1



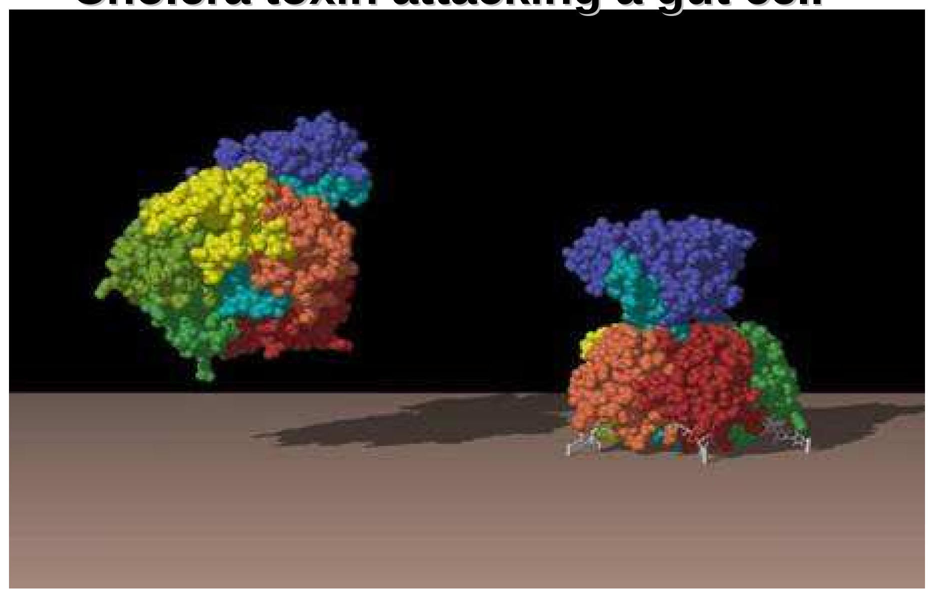
39 nm 3:1

Chemistry and Biology

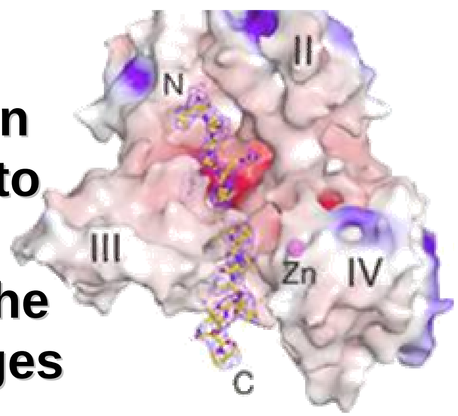


Measuring very low levels of mercury in fish and determining its chemical form.

Cholera toxin attacking a gut cell

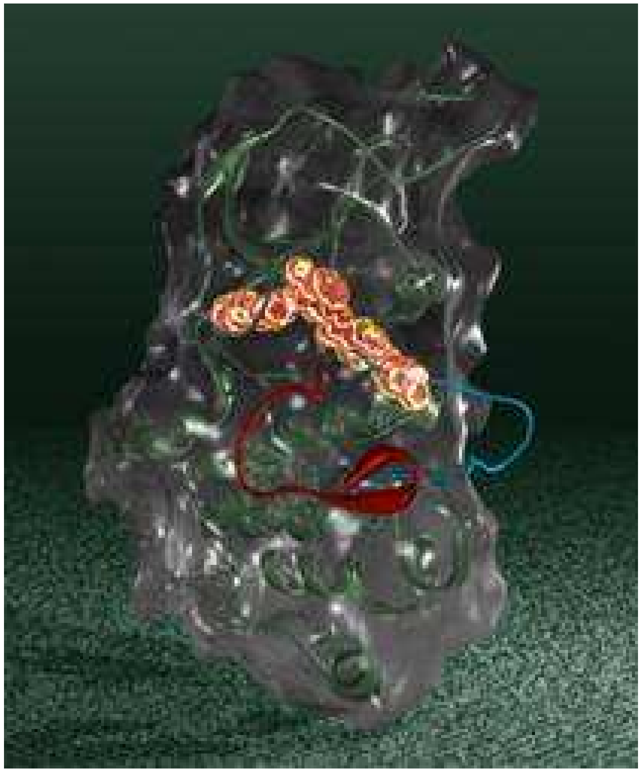


Studying Anthrax Toxin components to develop treatment in the advanced stages of infection.



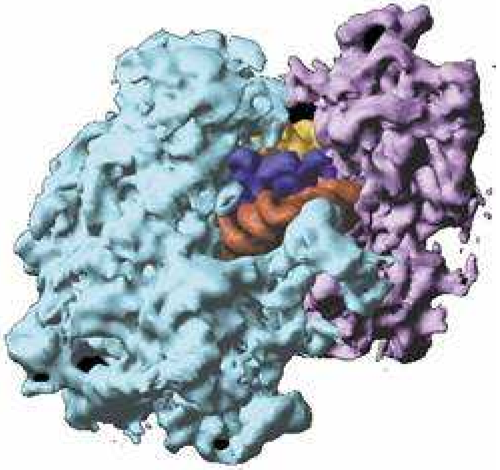
Protein Crystallography

Drug Design
GLEEVEC



Leukemia

Understanding how protein's are made

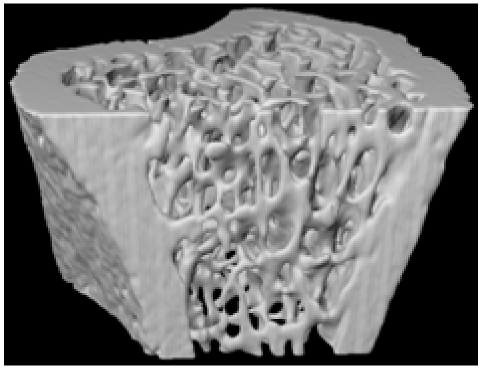


Ribosomes make the stuff of life. They are the protein factories in every living creature, and they churn out all proteins ranging from bacterial toxins to human digestive enzymes

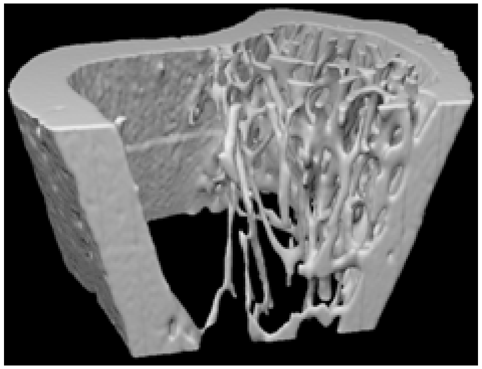
Cellular Imaging

This is an image taken with the x-ray microscope of a malaria-infected blood cell. Researchers at Berkeley Lab use pictures like this to analyze what makes the malaria-infected blood cells stick to the blood vessels.

Biomedicine



before estrogen loss



after estrogen loss

Studies of osteoporosis at SSRL

These studies make use of the penetrating power of X-rays, rather than their short wavelength

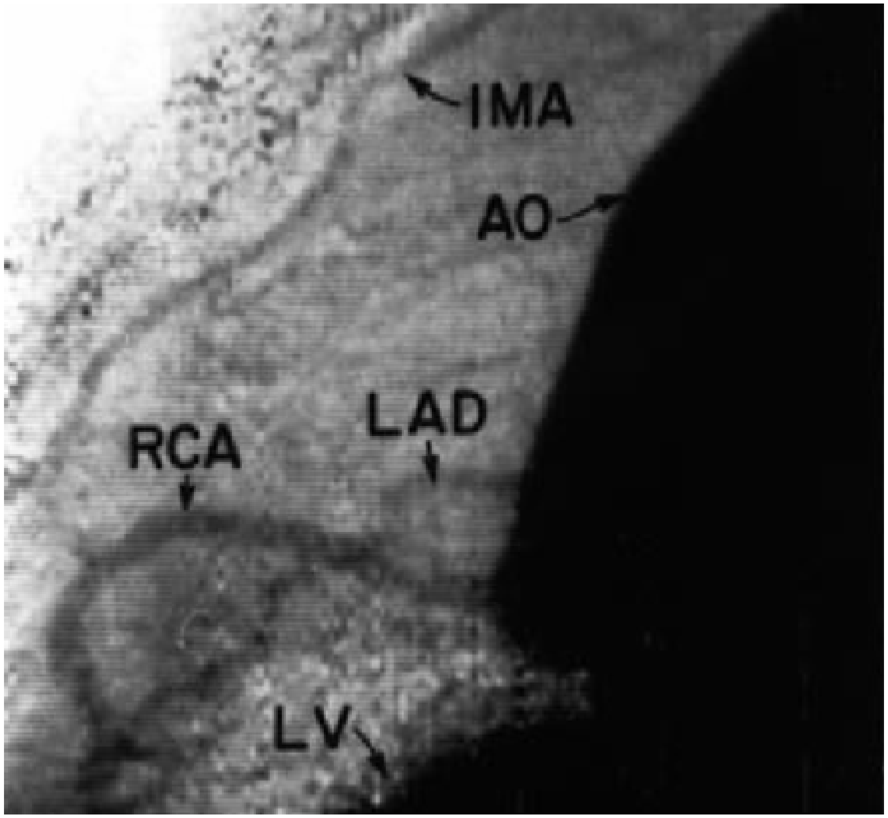


Image of a human coronary artery taken with synchrotron radiation at SSRL

Art & Archaeology

Sulfuric acid causing the decay of the *Vasa*, the Swedish warship which sank in Stockholm harbor in 1628

Virgin, Child, and Saint John **A renaissance panel painting by Jacopo Sellaio or Filippino Lippi being restored at the Cantor Art Center**

X-rays have enabled seminal scientific discoveries

18 Nobel Prizes Based on X-ray Work

Chemistry

1936: Peter Debye

1962: Max Purutz and Sir John Kendrew

1976 William Lipscomb

1985 Herbert Hauptman and Jerome Karle

1988 Johann Deisenhofer, Robert Huber and Hartmut Michel

1997 Paul D. Boyer and John E. Walker

2003 Peter Agre and Roderick Mackinnon

Physics

1901 Wilhem Rontgen

1914 Max von Laue

1915 Sir William Bragg and son

1917 Charles Barkla

1924 Karl Siegbahm

1927 Arthur Compton

1981 Kai Siegbahn

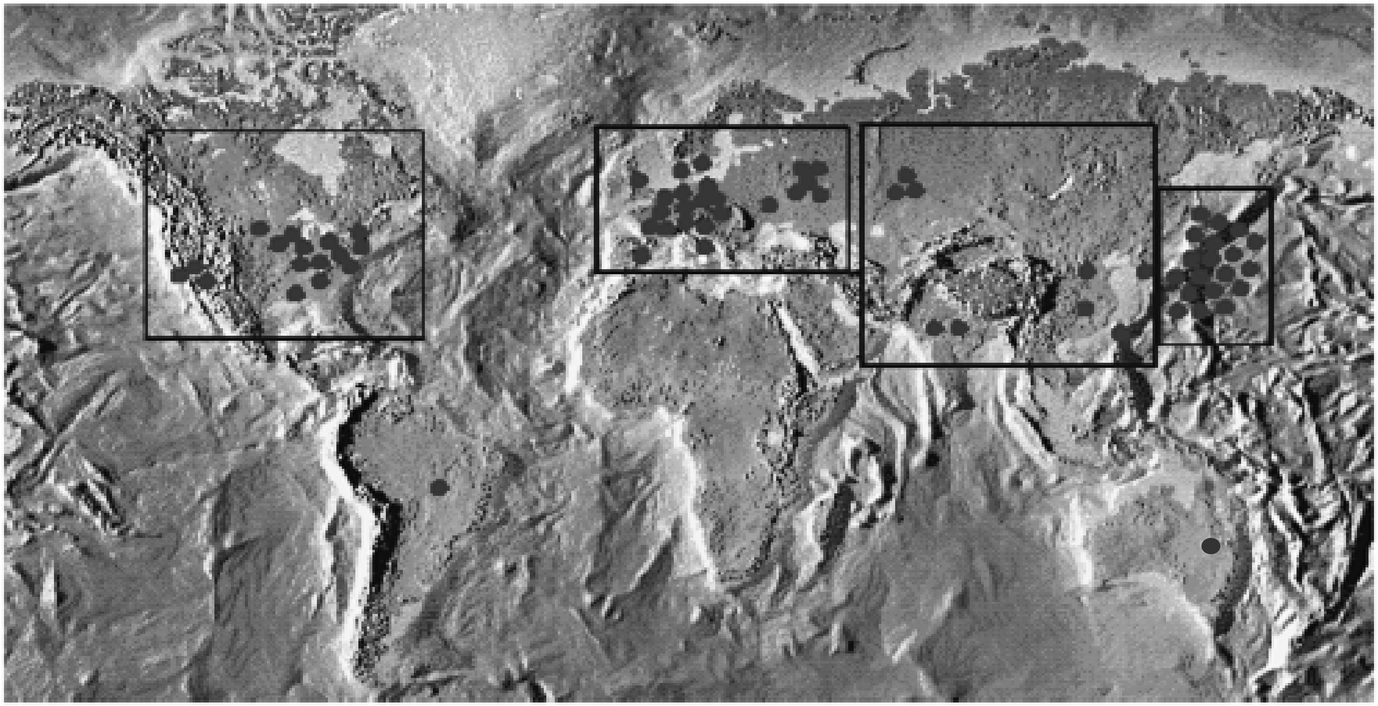
Medicine

1946 Hermann Muller

1962 Frances Crick, James Watson and Maurice Wilkins

1979 Alan Cormack and Godrey Hounsfield

20 000 Users World-Wide

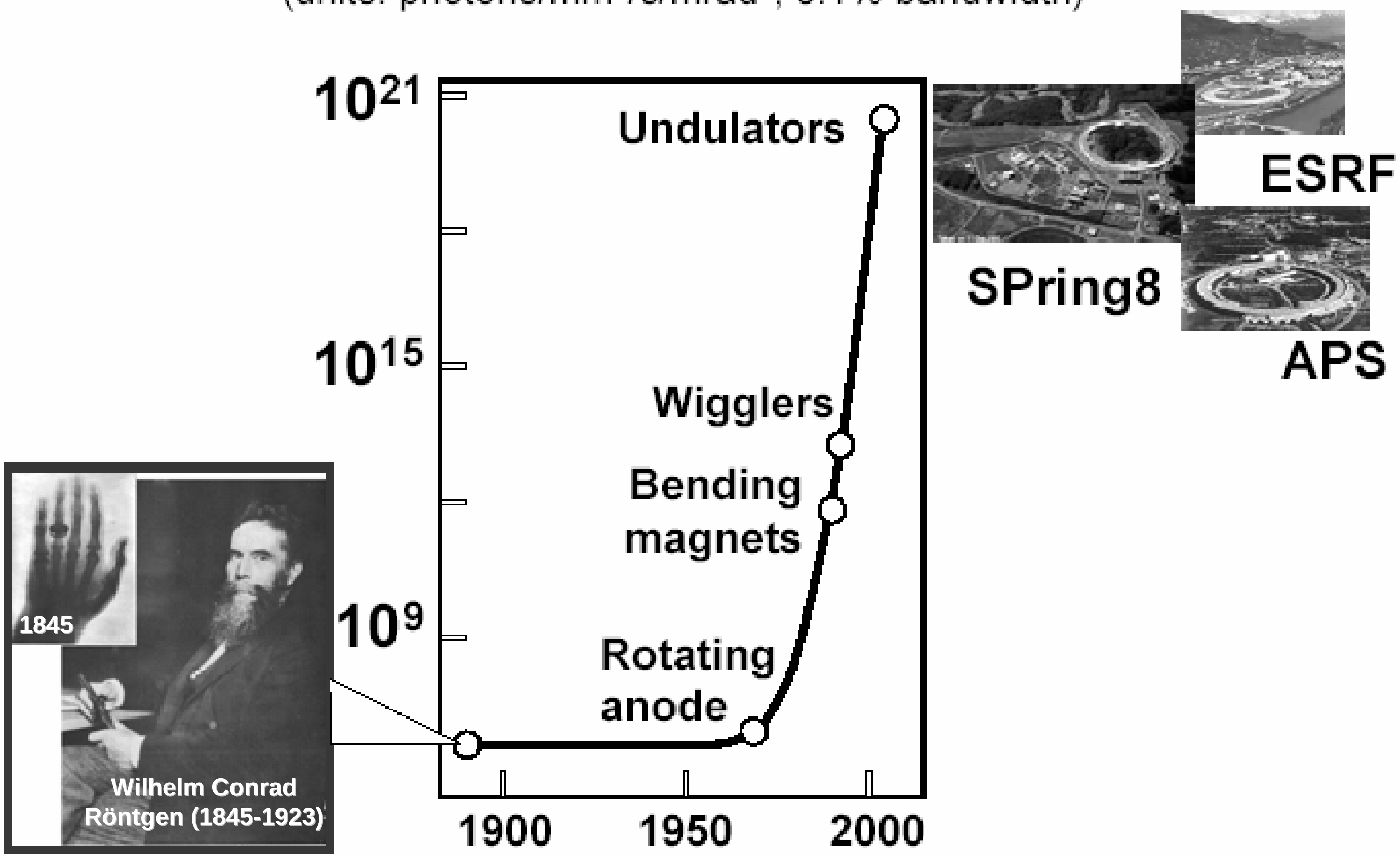


- **54 in operation in 19 countries used by more than 20,000 scientists**
- **8 in construction**
- **11 in design/planning**

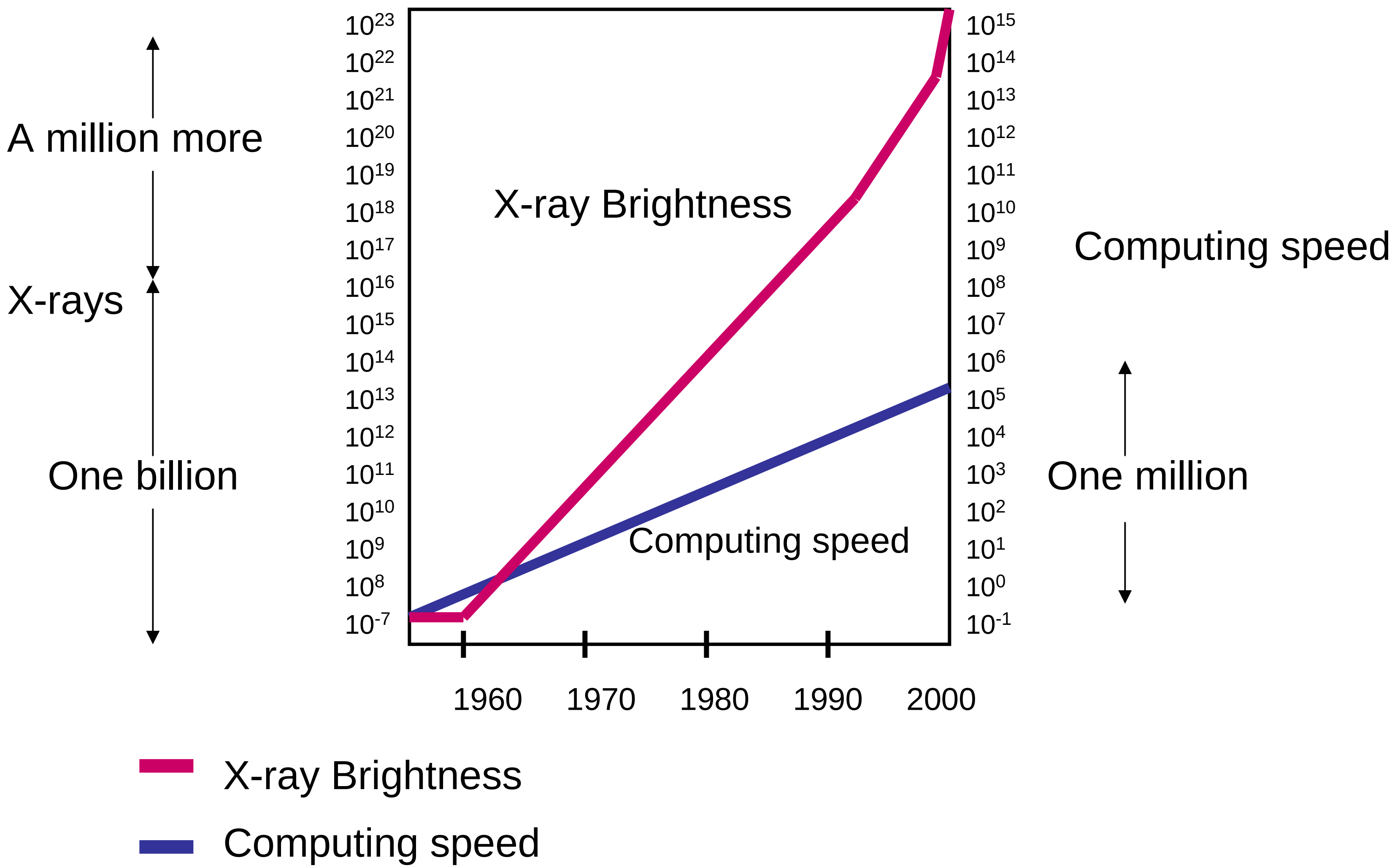
For a list of SR facilities around the world see
http://ssrl.slac.stanford.edu/SR_SOURCES.HTML
www.sesame.org.jo

Steep Growth in Brightness

(units: photons/mm²/s/mrad², 0.1% bandwidth)



Growth in X-ray Brightness Compared to Growth in Computing Speed



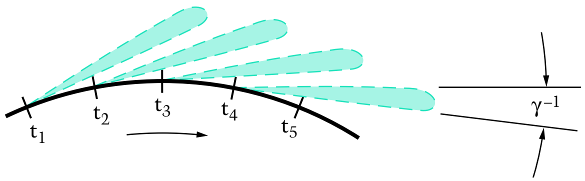
How to Optimize a Synchrotron Light Source

- **The ultimate performance parameter of a synchrotron light source is the brightness.**

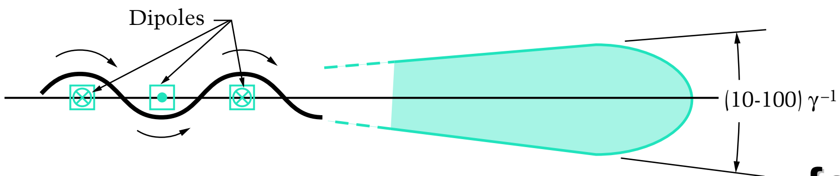
- **The battle for the brightness maximization is fought in two fronts:**
  - **In the storage ring, by increasing the current and designing new lattices capable of smaller emittances. Current of hundreds of mA and lattices with ~ 1 nm emittance are presently used.**
  - **In the ring elements where the synchrotron radiation is actually generated: dipole magnets and insertion devices. And this is where spectacular improvements have been achieved!**

- **Light sources are usually classified for increasing brightness as:**
  - ***1st generation*: x-ray tubes.**
  - ***2nd generation*: "parasitic" synchrotron radiation sources from dipoles in colliders.**
  - ***3rd generation*: dedicated storage rings with insertion devices**
  - ***4th generation*: free electron lasers**

How Synchrotron Radiation is Generated in Storage Rings



bending magnet



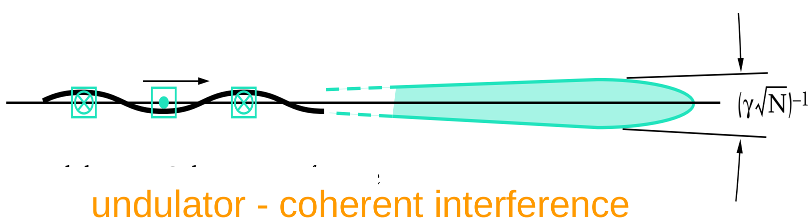
wiggler - incoherent superposition

Continuous spectrum characterized by ε_c = critical energy

$$\varepsilon_c(\text{keV}) = 0.665\ B(\text{T})E^2(\text{GeV})$$

***For example*:**

for B = 1.35 T E = 2 GeV ε_c = 3.6keV



undulator - coherent interference

Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_U}{\gamma^2} \quad \textbf{(fundamental)}$$

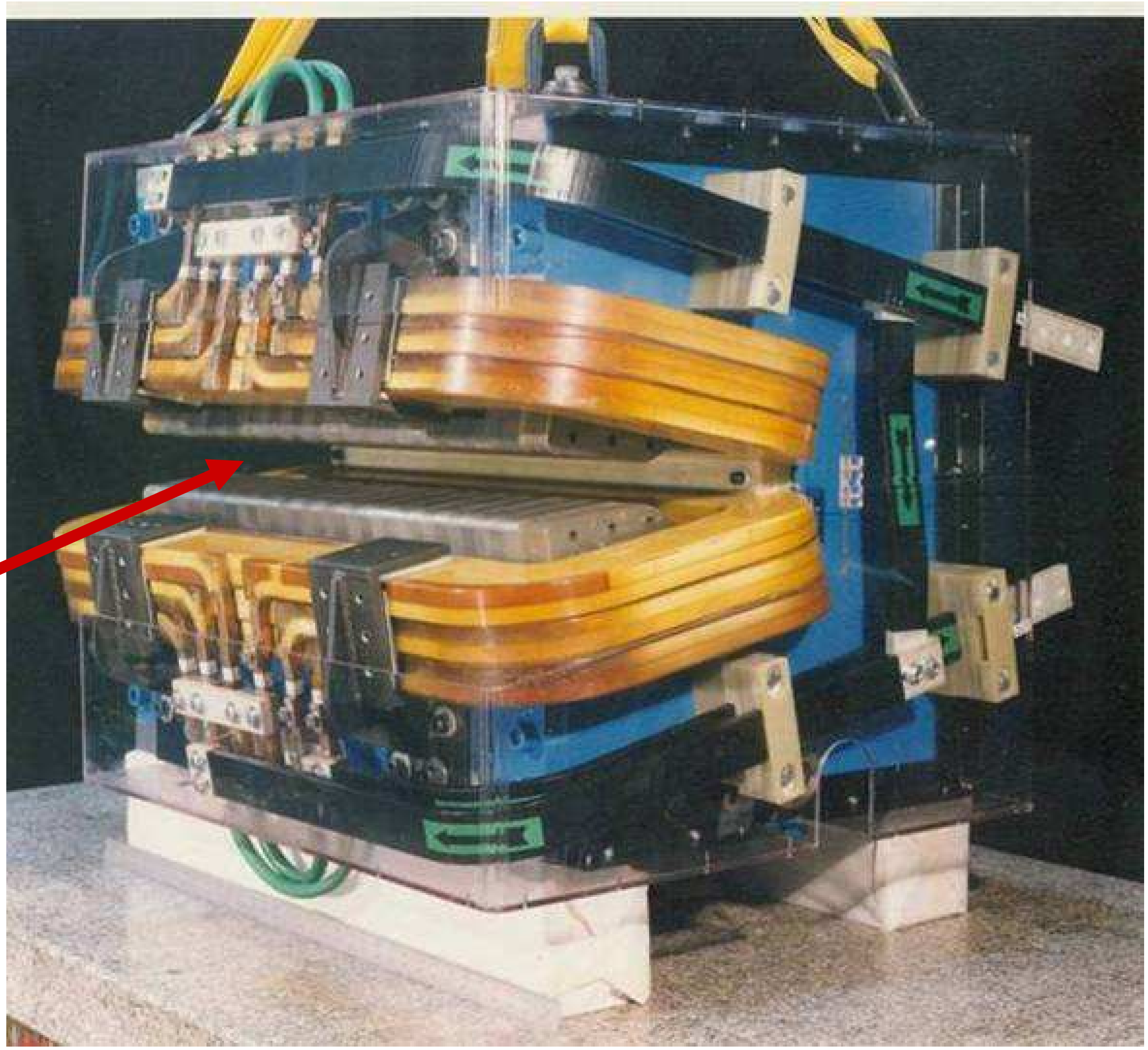
$$\varepsilon_1\ (\text{keV}) = \frac{0.95\ E^2\ (\text{GeV})}{\lambda_u{}^{(\text{cm})}\ \left(1 + \frac{K^2}{2}\right)}$$

$K = \gamma\varphi$ **where φ is the angle in each pole**

+ harmonics at higher energy

Bend Magnet

Normal-Conductive
~ 1.5 T Max



"C" shaped for allowing to the radiation to exit

Bend Magnet Synchrotron Radiation Spectrum

Spectrum:

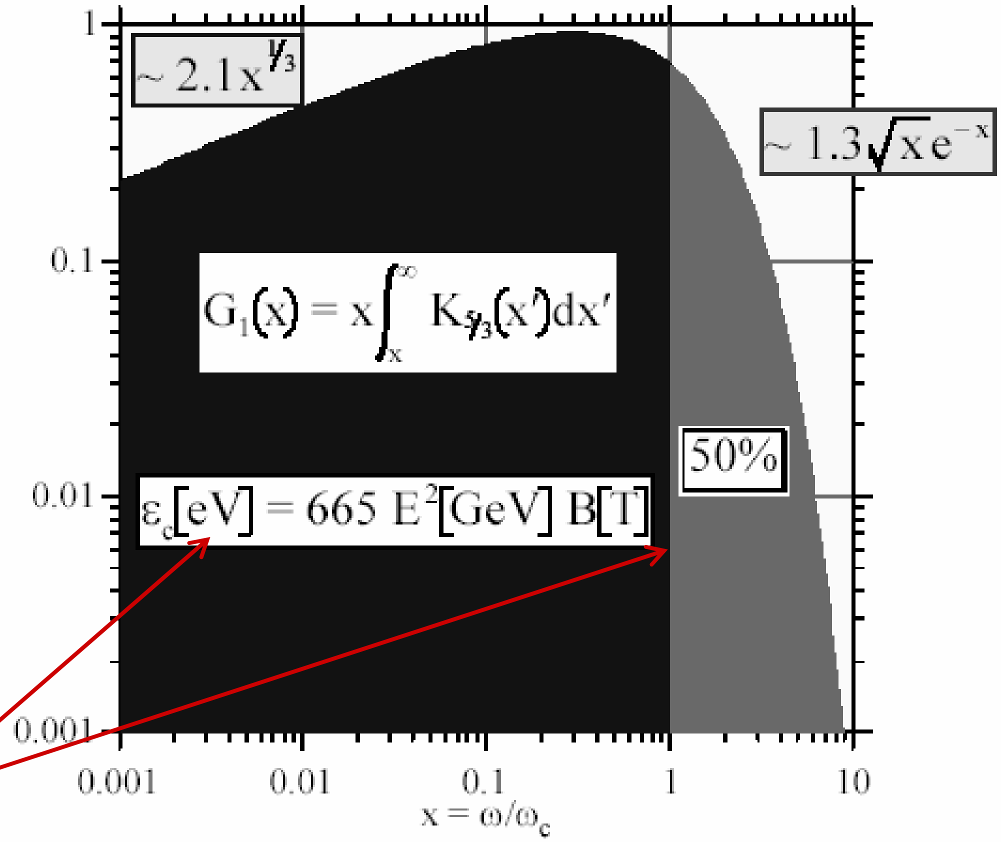
$$\frac{dP}{d\omega} = \frac{P_{tot}}{\omega_c} S\left(\frac{\omega}{\omega_c}\right)$$

Universal function

$$S(x) = \frac{9\sqrt{3}}{8\pi} x \int_x^\infty K_{5/3}(x')dx' \qquad \int_0^\infty S(x')dx' = 1$$

$$P_{tot} = \frac{2}{3} \hbar c^2 \alpha \frac{\gamma^4}{\rho^2}$$

$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$



Critical frequency

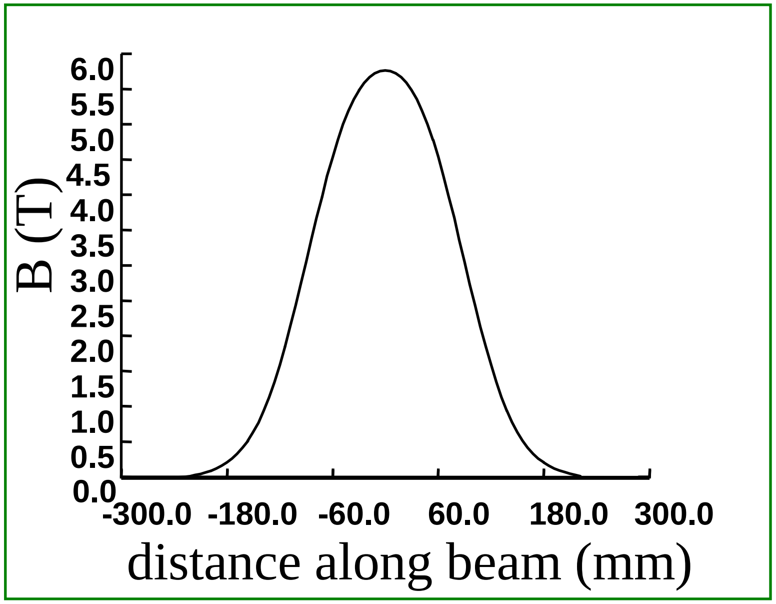
Dipoles for Hard X-rays

At the Advanced Light Source three of the existing thirty six 1.3 T dipoles were replaced by three 5 T superconducting dipoles ("superbends").

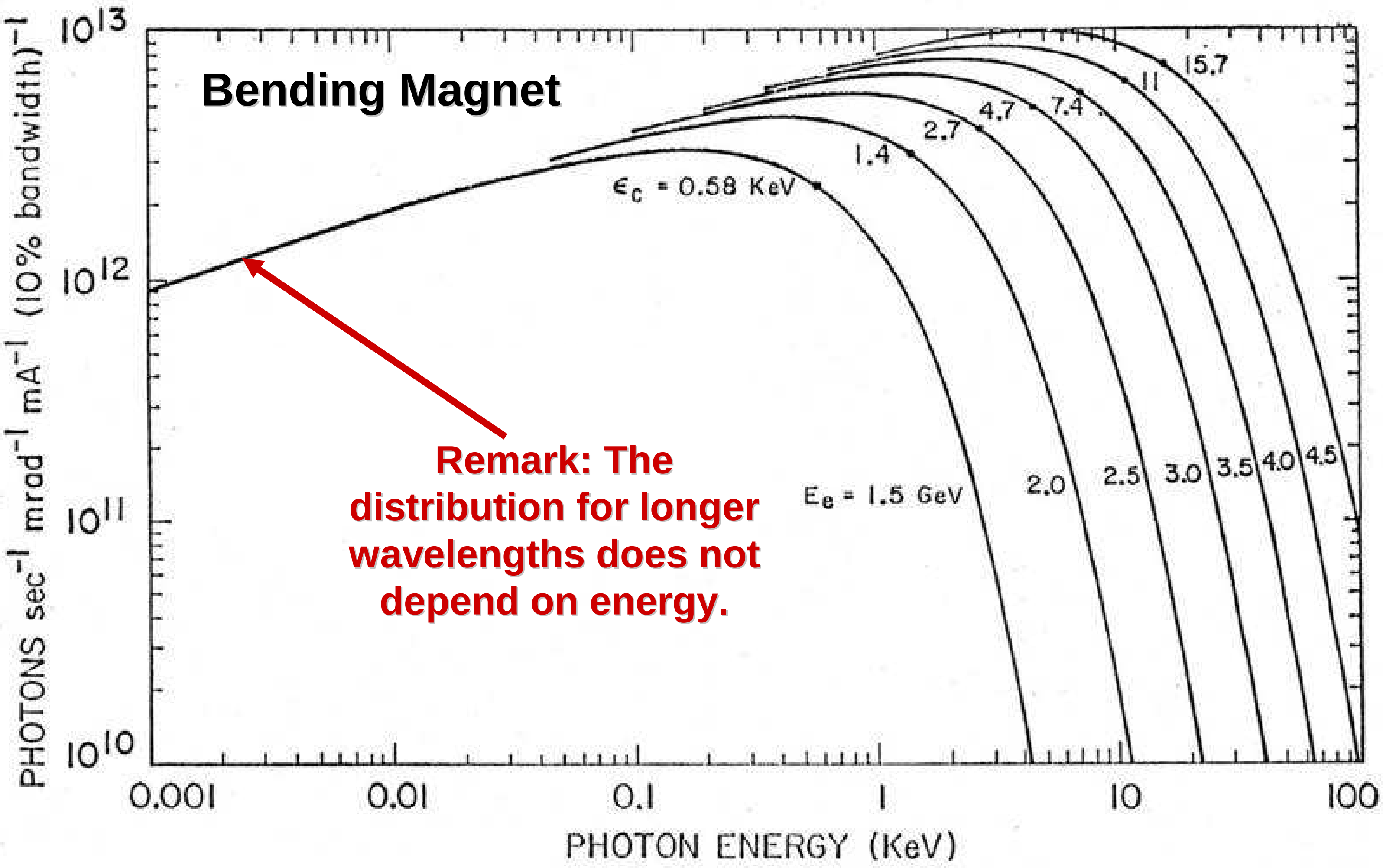
Superbend with cryostat

Superbend without cryostat

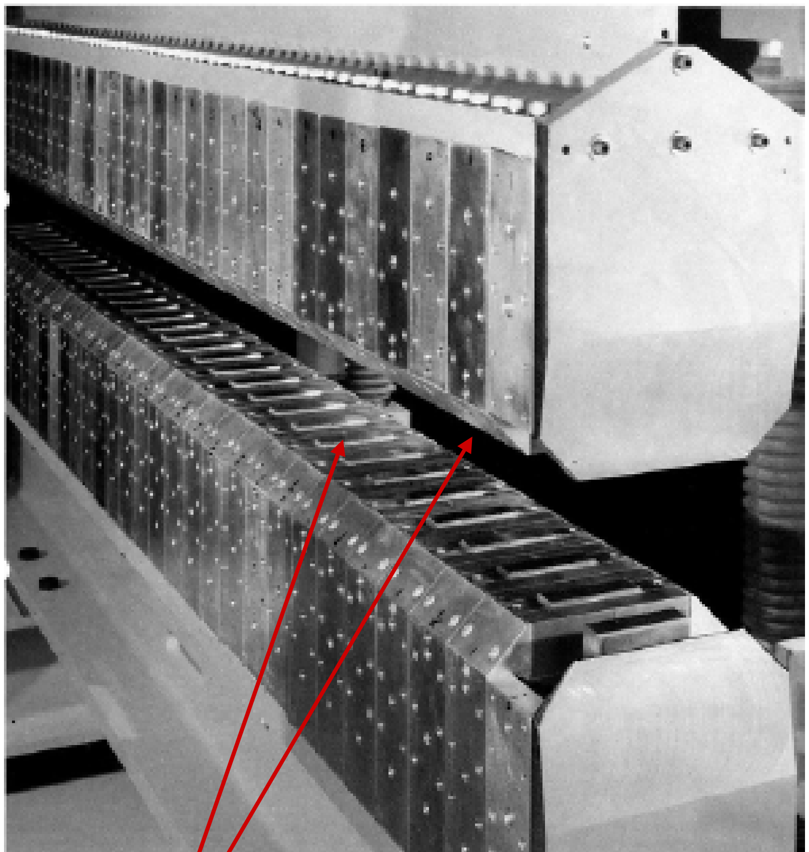
Superbend magnetic field



Spectrum Energy Dependency

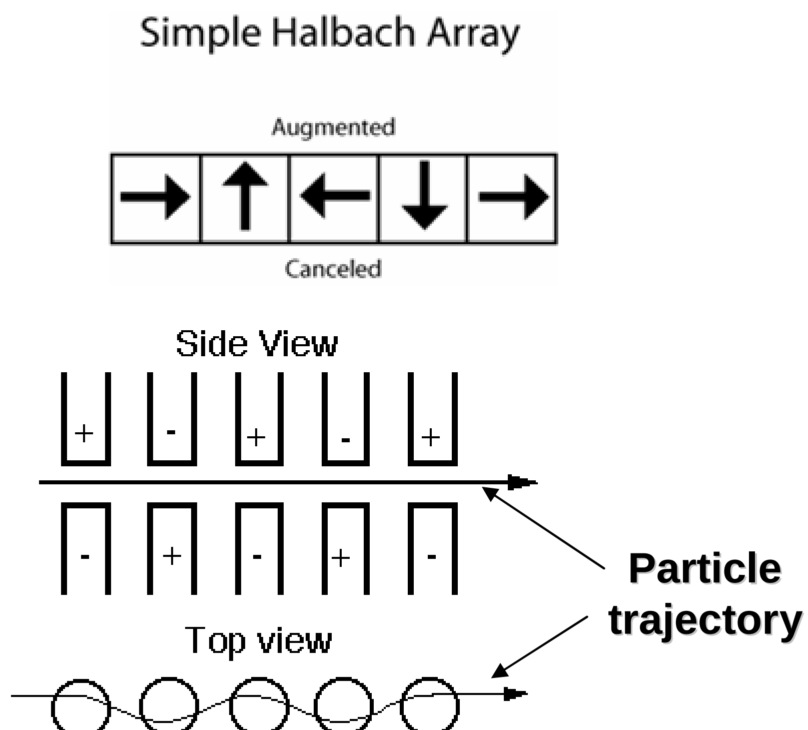


Planar Undulators

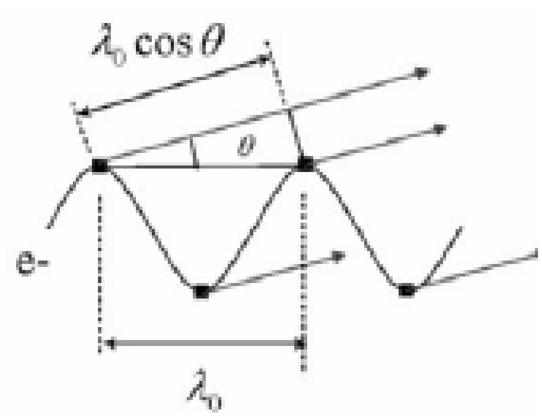


Permanent Magnets

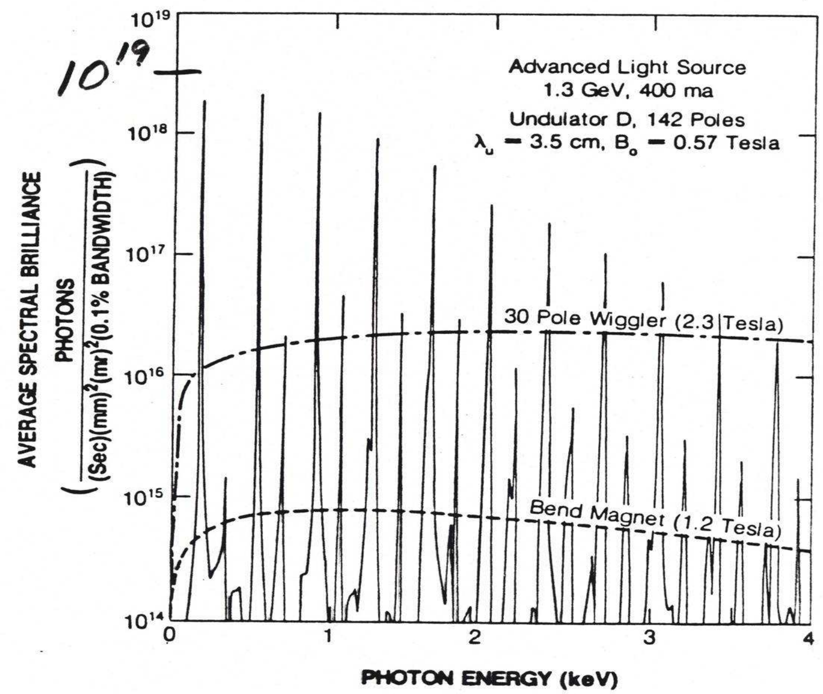
Invented by Klaus Halbach



Undulator Radiation



$$\lambda = c\left(\frac{\lambda_0}{v_z} - \frac{\lambda_0}{c}\cos\theta\right) \cong \lambda_0\left(1 - \frac{v_z}{c} + \frac{\theta^2}{2}\right) \cong \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$



Photons emitted by different poles interfere transforming the continuous dipole-like spectrum into a discrete spectrum

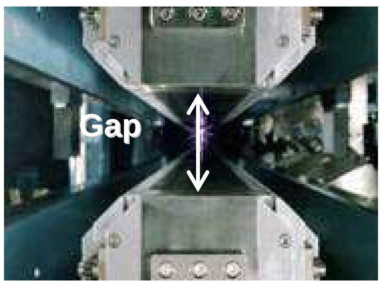
The interference condition requires that, while traveling along one period of the undulator, the electrons slip by one radiation wavelength with respect to the (faster) photon.

From Undulator Radiation to Wiggler Radiation

The spectrum of the undulator radiation: $\lambda_1 = \dfrac{\lambda_U}{2\gamma^2}\left(1+\dfrac{K^2}{2}\right) \quad 1^{st}\ \ harmonic$

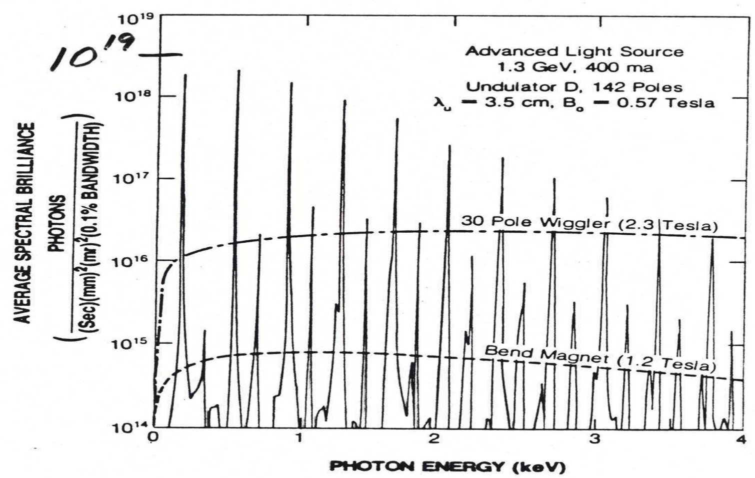
depends strongly on the strength parameter *K*: $K = \gamma\varphi \quad where\ \ \varphi \approx \dfrac{\lambda_U}{2\rho} \quad is\ the\ bending\ angle\ in\ each\ pole$

Remembering that: $\rho = \dfrac{\gamma\beta m_0 c}{eB}$ **One can see that *K* is proportional to the field *B*:** $K \approx \dfrac{e}{2m_0 c}\lambda_U \dfrac{B}{\beta}$



In a permanent magnet undulator, *B* and consequently *K* can be modified by changing the gap height. The larger the gap the lower the field.

When *B* is increased, both *K* and the "wiggling" inside the undulator increase as well. With the larger wiggling, the overlap between the radiated field (1/γ cone) decreases and the interference is reduced. For $K >> 1$ no interference is present and the undulator presents the continuum spectrum typical of the wiggler.

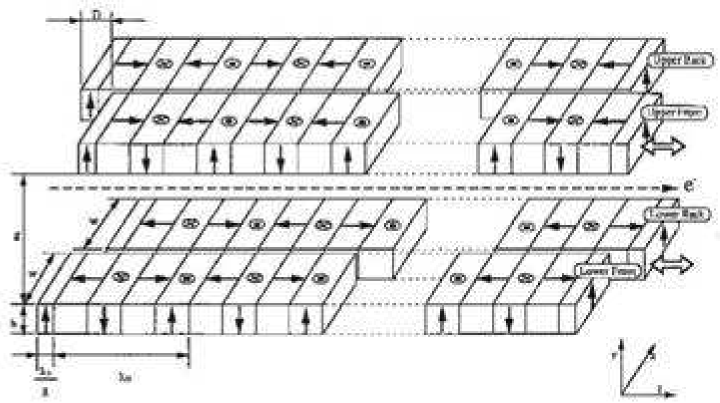


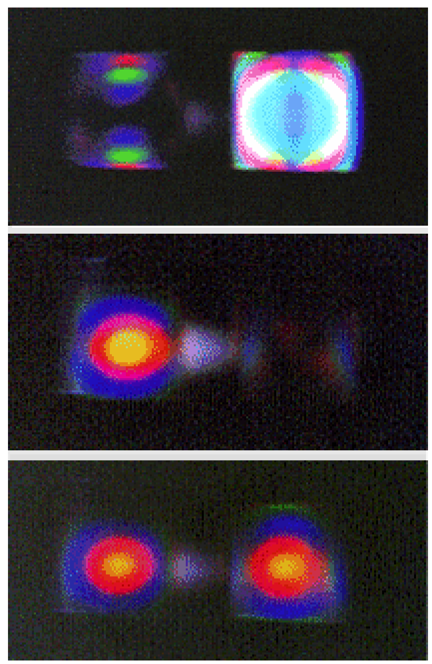
Elliptically Polarizing Undulators

ALS EPU50 (1998)

Pure permanent magnet technology, Elliptically polarizing capability.

The arrays of permanent magnets can be mechanically shifted modifying the polarization of the radiated light.

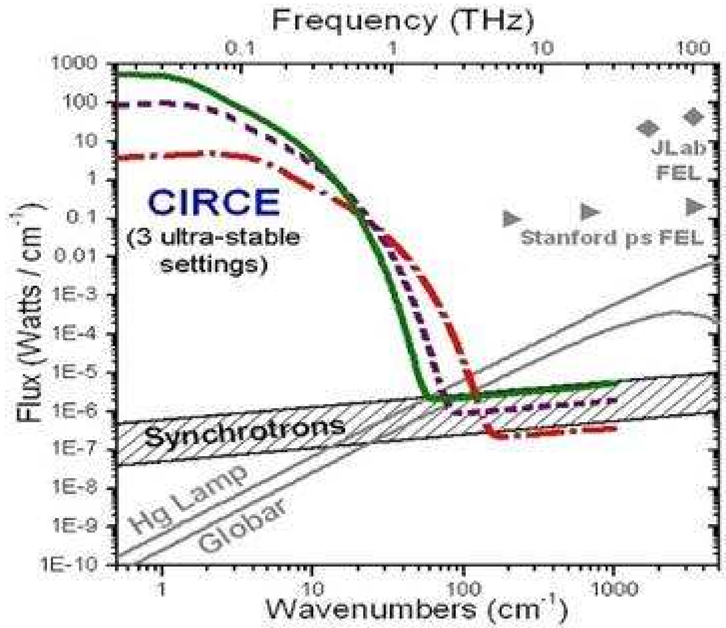


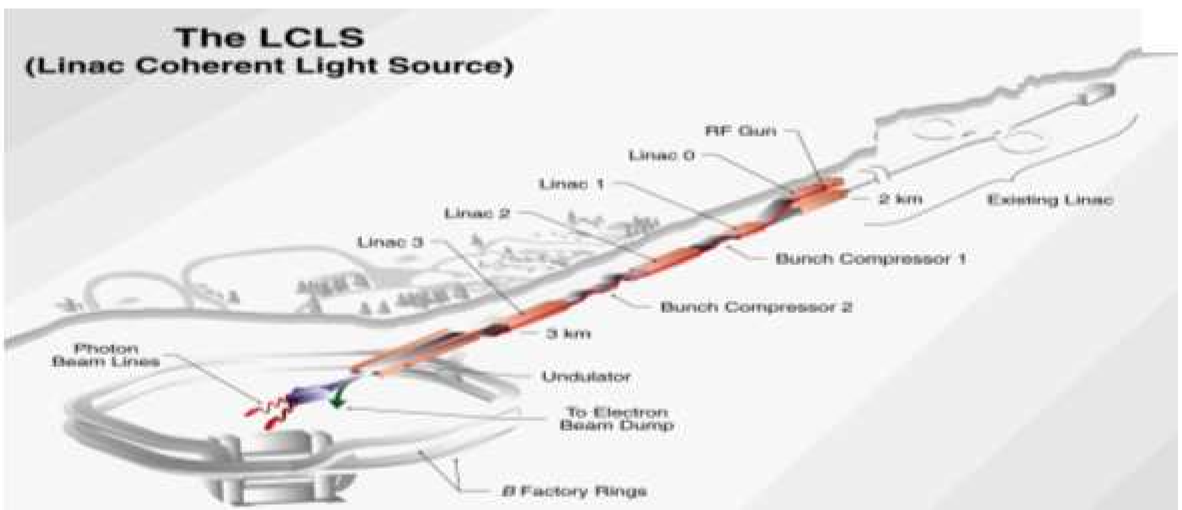


Such a device allows for the complete control of the polarization from linear in to elliptical.

Future of Synchrotron Radiation

- **Higher Brightness**
  - **- Free Electron Lasers**
- **Shorter Pulse Lengths**
  - **- Femto (10^{-12}) and Attosecond (10^{-15})**
- **Terahertz (T-rays)**
  - **- Coherent Synchrotron Radiation**





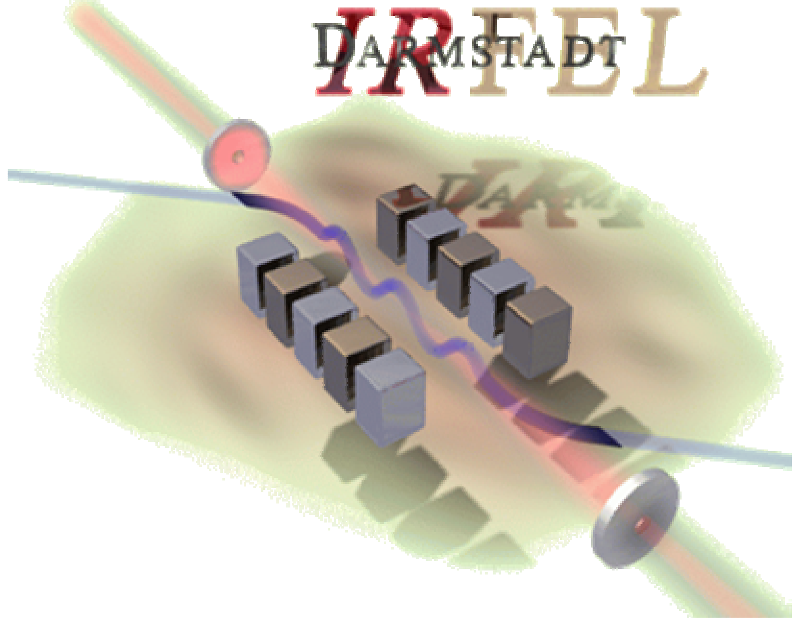
... (?)

Free Electron Laser Basics

• In free electron lasers (FEL), a relativistic electron beam and a laser overlap and travel simultaneously inside an undulator.

• The laser is tuned at the frequency of one of the undulator harmonics. The whole undulator is included inside an optical cavity composed by two reflecting mirrors located at the two undulator extremes.

•In such a schemes the laser beam bounces many times back and forward inside the cavity and has multiple interactions with the electron beam.



• Oscillating through the undulator, the electron bunch interacts with the laser and in a minor way with its own electromagnetic field created via spontaneous emission. Depending on the relative phase between radiation and electron oscillation, electrons experience either a deceleration or acceleration.

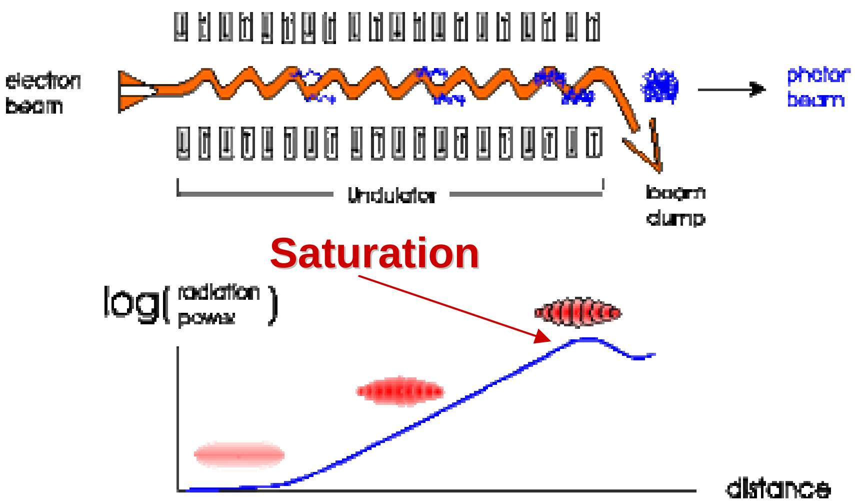
• Through this interaction a longitudinal fine structure, the so called **micro-bunching**, is established which amplifies the electromagnetic field at the laser frequency.

The SASE FEL Scheme

• In the self-amplified spontaneous emission (SASE) FEL, there is no laser and the electron beam interacts only with its own spontaneous emission.

• For such a scheme to work, one has to guarantee a good electron beam quality and a sufficient overlap between radiation pulse and electron bunch along the undulator. To achieve that, one needs a low emittance, low energy spread electron beam with an extremely high charge density in conjunction with a very precise magnetic field and accurate beam steering through the undulator.

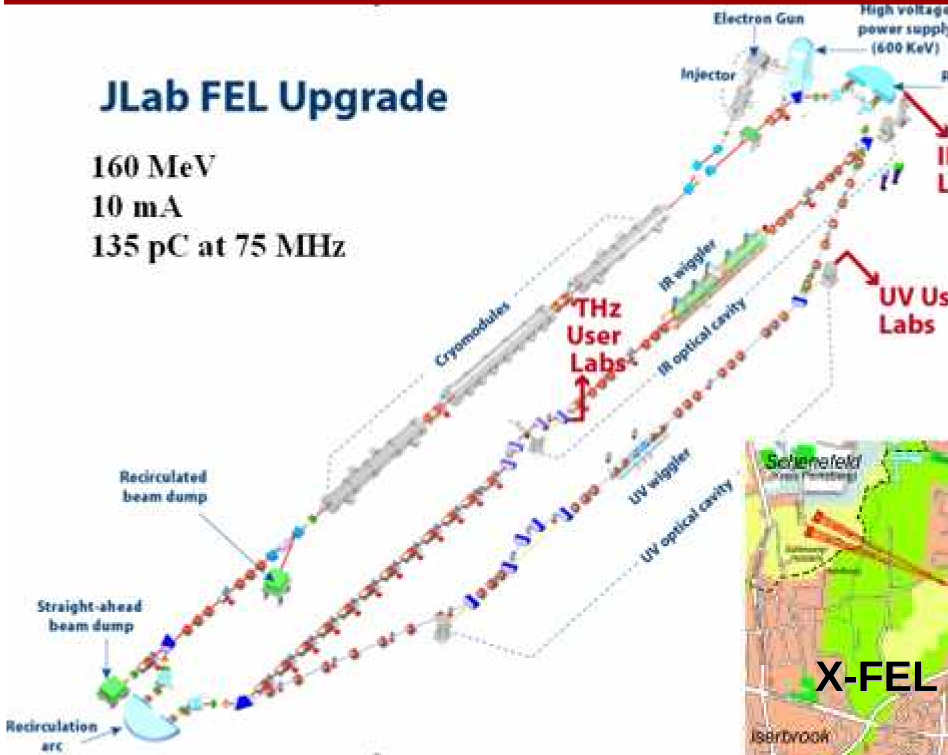
• In order to obtain a large gain in the SASE scheme, a long and expensive undulator is required. In a "conventional" FEL the undulator is much shorter because the laser beam is re-circulated many times inside the cavity. Unfortunately, the highest frequency achievable with such a configuration is limited to the near-UV because of the absence of efficient large incidence angle mirrors for shorter wavelengths.

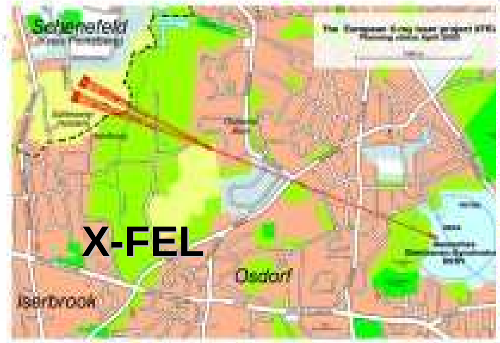


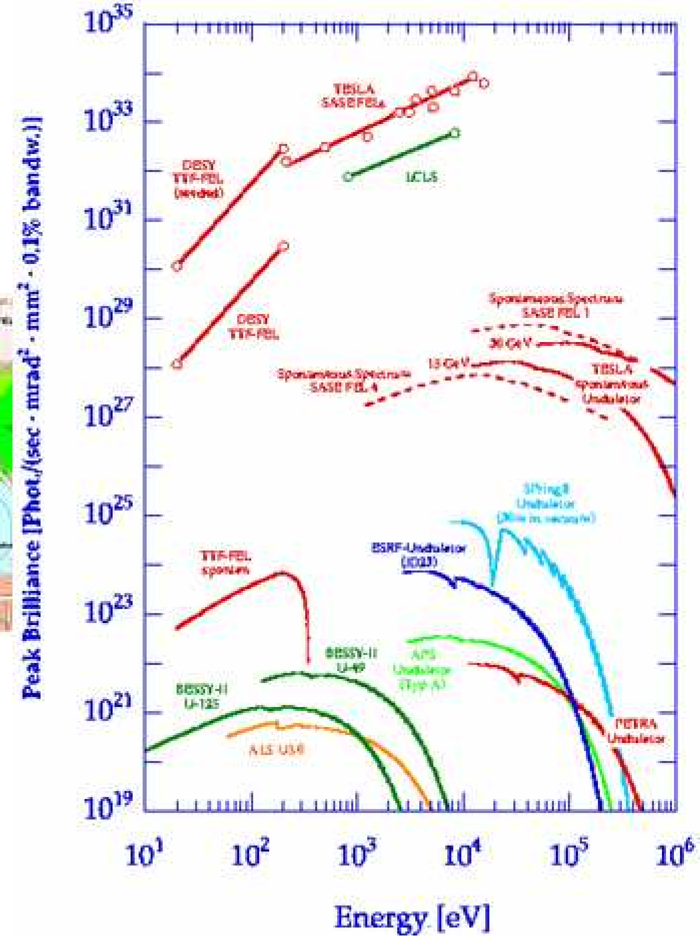
(Some) FEL Projects

JLab FEL Upgrade

160 MeV
10 mA
135 pC at 75 MHz







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- Brunnen, Switzerland, 2 – 9 July 2003

  http://cas.web.cern.ch/cas/BRUNNEN/lectures.html

- **Technical Design Report (TDR) for TESLA, Part V *The X-ray free electron laser***

Possible Problems

• Calculate the critical energy in eV for the ALS superbends knowing that the electron beam energy is 1.9 GeV, the field is 5 T and the total deflection angle for the magnet is 10 deg. Remember that the photon energy is given by hf (with h the Planck constant, 6.626068×10^{-34} m^2 kg / s, and f the photon frequency)

• Always for the ALS case, calculate the critical energy for the normal bends knowing that the bending radius is 4.957 m and the total deflection angle for the magnet is 10 deg.

• Using the universal spectrum for the bending magnet radiation, calculate for both the above cases, the maximum radiated power in 0.1% bandwidth when 400 mA electrons are stored (the ring length is 197 m). Indicate at which photon energy is the maximum located.